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The commuting distribution

Abstract: In this paper we analyse the commuting distribution from a job search perspective. We have examined under which conditions the commuting distribution is unimodal which is one of the stylised facts of commuting. It appears that a necessary condition is that space is two-dimensional. Furthermore, one of the following ingredients is sufficient: on-the-job mobility, spatially-differentiated search or heterogeneity of jobs. Residential mobility does not appear to explain the shape of the commuting density function as we observe it.
<u>JEL classification</u>: *R20, R64, J64; Keywords: commuting, search, mobility.*

1. Introduction

Assuming the existence of a simplified static world with perfect markets, a utility maximising individual accepts the costs of the work trip, because the marginal commuting costs are compensated for by marginal benefits in the labour market (e.g. higher wages) and housing market (e.g. lower rents). The assumption that labour and housing markets are perfect has been frequently criticised (e.g. Anas, 1982; Hamilton, 1982, 1989). In particular, it has been argued that imperfect information about job opportunities and the presence of residential moving costs are ignored.[1] Under the perfect market assumption, workers would adjust their residence or workplace location so that the costs due to commuting are minimised.[2] In an economy with market imperfections, however, this will rarely be the case (Weinberg et al., 1981; Zax, 1991; Holzer, 1994). This suggests that our understanding of commuting behaviour may be improved by focusing on market imperfections.[3] This paper starts from the basis that the lack of information about job opportunities implies that individuals who search

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[1] An essential characteristic of the labour market is therefore that individuals have to search for jobs. A large number of studies is concerned with the empirical analysis of commuting distance or time (e.g. White, 1986; Rouwendal and Rietveld, 1994; Benito and Oswald, 1999; Van Ommeren et al., 1999). A notable result of these studies is that the reported R^2 is typically very low. For example, White (1986) analyses commuting times of males and females and reports a R^2 of 0.04. In a similar analysis, Benito and Oswald (1999) report a R^2 of 0.18 although 68 explanatory variables are included. This suggests that commuting is mainly an outcome of a stochastic process. The observed commute is then the result of a process in which the lack of information plays an important role.

[2] As is nowadays well known Hamilton (1982) raised the question of whether, or not, commuting in US metropolitan areas is inefficient. He argued that 10 times more commuting actually occurs in metropolitan areas than is predicted by urban economic models. Cropper and Gordon (1991), Small and Song (1992) and Kim (1995) also provide evidence that more commuting occurs than the minimum amount required for workers to commute between metropolitan area's existing houses and its existing jobs, but the best evidence suggests that the ratio of actual to minimum commuting is around 2.5 or even less (Kim, 1995). Overall, the "wasteful" commuting controversy has shown that workers on average commute too much, but the amount of extra commuting may be lower than previously thought.

for a job are confronted with spatial distribution of acceptable job opportunities. The aim of this paper is to analyse the characteristics of the commuting distribution given the assumption that individuals are confronted with a *spatial distribution of job offers*. We believe that the commuting distribution is theoretically of interest. The main reason is that we can observe it, so we can use it to test the relevance of theories used to explain commuting behaviour. One of the stylised facts is that the commuting distribution is unimodal (e.g. Stutzer and Frey, 2003; Benito and Oswald, 1999). In empirical studies, it is often found that the distribution can be best described by a lognormal or a gamma distribution (e.g. Rouwendal and Rietveld, 1994; Russo, 1996; Van Ommeren et al., 1999). By focusing on the distribution, instead of focusing on the mean which is more common, it is easier to test for competing theories.[4] It turns out that assumptions on the dimensions of space are essential to derive the characteristics of commuting distribution.[5] Given absence of full information on the availability of jobs, the difference is crucial. For example, given two-dimensional space and at random search, the probability of finding a job at a certain distance is an increasing function of distance, whereas given one-dimensional space this probability does not depend on distance. As a consequence, the form of the commuting distribution is structurally different for different assumptions on the dimension of space.

We will analyse the functional form of the commuting distribution using search theory (see also Rouwendal and Rietveld, 1994; Rouwendal, 1998; Manning, 2003). Initially, we will presume homogeneous space with search frictions and examine the role of on-the-job mobility, spatial search residential mobility and heterogeneity of jobs on the form of the commuting distribution.[6] We demonstrate under which circumstances a unimodal commuting distribution emerges. It appears that we need the condition that space is two-dimensional. Furthermore, one of the following ingredients is sufficient: on-the-job mobility, spatially-

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[3] Crane (1996) shows that uncertainty concerning job locations increases the ratio of actual-to-minimum commuting in urban areas.

[4] For example, it has been found frequently that the length of the employment spell reduces the commute (see, e.g. White, 1986), because it is argued that during a longer employment spell, it is more likely that a worker will reduce the commute by moving residence. However, other interpretations of this effect are also possible. For example, it may be argued that the causation is the other way round,because a longer commute induces job mobility. In the current paper, we derive the commuting distribution and examine the effect of residential mobility on the commuting distribution. Similarly, it has been found that recent school-leavers have longer commutes (ceteris paribus) than other workers, but by focusing on the commuting distribution we are able to generate more precise predictions.

[5] The difference between one- and two-dimensional space is often ignored, maybe because in static (urban) models, the difference is of no importance.

[6] The commuting distribution will be shown to be the result of the presence of residential moving costs and the job seekers' lack of information about job opportunities. If moving residence would be costless or when job seekers have full information on the location of the nearest job vacancy, one would observe a degenerate commuting distribution.

differentiated search or heterogeneity of jobs. It appears further that by presuming, that the employment density is linearly increasing over space, so space is homogenous, the shape of the commuting distribution does not fundamentally change. Futher, allowing for residential mobility does not contribute much to explain the shape of the commuting distribution as we observe it.

The outline of the paper is as follows. In Section 2, we introduce a basic labour market model to derive commuting density functions. We proceed by presuming homogeneous space, where workers search at random for identical jobs, and residential mobility is absent. In Section 3, 4 and 5, we will introduce spatially-varied search effort, and allow for residential mobility and heterogeneity of jobs. In Section 6, we relax the assumption of homogeneous space.

2. The basic labour market model

In the basic model, all jobs are identical and pay the same wage w but differ with respect to the distance to the residence location, and therefore with respect to the commuting costs. The commuting costs are proportional to the commuting distance t and can be written as ηt. To keep matters simple, we initially assume that space is homogeneous, so every point in space has the same level of employment and population (see also Manning, 2003).[7] Each worker is either unemployed (state 0) or employed (state 1). At random time intervals, an unemployed worker receives job offers randomly from each point in space at a rate λ_0, an employed worker at rate λ_1. The commuting distance implied by a job offer is assumed to be a realisation of a random draw from the cumulative employment density function $F(t)$, where $F(t)$ is the proportion of vacancies (employment offers) at a commuting distance no greater than t. The corresponding employment density function will be denoted as $f(t)$. Given one-dimensional space, $F(t) = \alpha t$; given two-dimensional space, $F(t) = \beta t^2$. Workers must accept or reject job offers as soon as they arrive. Given this set up, *employed* workers will accept only job offers that reduce the commuting distance. We will see below that *unemployed* workers accept jobs with a certain range, defined by the maximum acceptable commuting distance T (see, similarly, Van den Berg and Gorter, 1997). We assume initially that workers do not move residence. Since space is homogeneous, the arrival rate of jobs is infinite, but the job moving rate will be finite, since not all jobs are accepted.

[7] Although the assumption of homogeneous space seems restrictive, it is important to realise that the homogeneous space assumption only has to hold within the area of search, which is a far less restrictive

We assume that employed workers are dismissed and thus become unemployed at rate δ.[8] Any unemployed worker receives utility flow b per instant (b can be interpreted as a benefit). All individuals discount future income at rate r. Given the above assumptions, the expected discounted lifetime income when an individual is unemployed, V_0, can be expressed as the solution to the following Bellman equation:

$$rV_0 = b + \lambda_0 [\int \max\{V_0, V_1(x)\} dF(x) - V_0]. \tag{1}$$

In words, lifetime income is equal to income while unemployed plus the expected gain in income attributable to finding acceptable jobs, where acceptance only occurs if the value of employment $V_1(t)$, exceeds that of continued search V_0. Similarly, the expected lifetime income of an employed worker who travels commuting distance t solves:

$$rV_1(t) = w - \eta t + \lambda_1 [\int \max\{V_1(x), V_1(x) - V_1(t)\}] dF(x) + \delta[V_0 - V_1(t)]. \tag{2}$$

As it can be shown that $V_1(t)$ is decreasing in t, whereas V_0 is independent of it, this implies that there exists for an unemployed worker a maximum acceptable commuting distance T, such that: $V_1(t) < V_0$ as $t > T$ and $V_1(t) > V_0$ as $t < T$.

Derivation of T is straightforward, since T is defined by $V_1(T) = V_0$. Equations (1) and (2) imply that:

$$rV_1(t) = w - \eta t + \lambda_1 \int_0^t [V_1(x) - V_1(t)] dF(x) + \delta[V_0 - V_1(t)] \tag{3}$$

and

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assumption. The assumption of homogeneous space within the area of search has some justification for the Netherlands (see Appendix 1).

[8] Given the employment density and at random job search, workers will be able to decrease the commuting costs over time by finding workplaces closer to their residence. A (sufficient) requirement for a non-degenerate equilibrium commuting distribution is then that some workers leave the population of employed workers and are replaced by new workers, which, on average, have higher commuting costs. In the current paper, we presume that workers are dismissed. An alternative interpretation is to presume that workers die, so δ is the mortality rate, which must be equal to the birth rate in the steady state.

$$rV_0 = b + \lambda_0 \int_0^T [V_1(x) - V_0] dF(x)\,. \tag{4}$$

An integration by parts implies then (see similarly Burdett and Mortensen, 1998):

$$\begin{aligned} T &= \frac{w-b}{\eta} + \frac{[\lambda_1 - \lambda_0]}{\eta} \int_0^T [V_1(x) - V_0] dF(x) = \frac{w-b}{\eta} + \frac{[\lambda_1 - \lambda_0]}{\eta} \int_0^T V_1'(x) F(x) dx \\ &= \frac{w-b}{\eta} - [\lambda_1 - \lambda_0] \int_0^T \frac{F(x)}{r + \delta + \lambda_1 F(T)} dx. \end{aligned} \tag{5}$$

It can be easily seen that if $\lambda_0 \neq \lambda_1$, then the maximum commuting distance depends on the employment density F. However if we follow Manning (2003) and presume that $\lambda_0 = \lambda_1$, the unemployed seeker will accept jobs for which holds that $w-\eta t \geq b$ and $T = (w-b)/\eta$. In this case, the unemployed accepts jobs as if he/she is myopic. If λ_1 exceeds λ_0, then $T > (w-b)/\eta$, so the unemployed may accept commuting distances for which hold that $w-t\eta < b$. The worker will accept a decrease in current income, because the worker is compensated by a higher job arrival rate when employed. The empirical evidence in the literature suggests however that in general $\lambda_0 > \lambda_1$. See, for example, Ridder and Van den Berg (1998) who estimate these parameters for a number of OECD countries. If λ_0 exceeds λ_1, then $T < (w-b)/\eta$, so the unemployed worker is more choosy.

Given the maximum acceptable commuting distance T, the flows into and out of unemployment are determined. Let u denote the steady state unemployment rate. In the steady state, the flow of workers into employment $\lambda_0 F(T) u$ equals the flow from employment to unemployment, $\delta(1-u)$, and therefore:

$$u = \frac{\delta}{\delta + \lambda_0 F(T)} \tag{6}$$

We denote the observed commuting distribution as G(t), where G(t) is the proportion of employed workers with a commuting distance no greater than t. This distribution differs from the cumulative employment density F(t).

Given the initial allocation of workers to firms, the number of employed workers at a distance no smaller than t, $[1-G(t)](1-u)$, can be calculated. In the steady state there must hold that:

$$\lambda_0[F(T)-F(t)]u = [\delta + \lambda_1 F(t)][1-G(t)](1-u)\,. \tag{7}$$

The left term on the left-hand side of (7) describes the flow of unemployed workers into jobs at a distance greater than t (but smaller than T), whereas the right-hand side represents the flow of jobs at a distance greater than t out into unemployment and into jobs smaller than t respectively. The unique steady-state commuting distribution function $G(t)$ can be written, using (6) and (7), as:

$$G(t) = 1 - \frac{1-F(t)/F(T)}{1+kF(t)}\,, \tag{8}$$

for $t \leq$ T, where $k = \lambda_1/\delta$. Hence, k is the ratio of the *employed* job arrival rate to the dismissal rate.

The above equation is insightful. In line with intuition, if $k = 0$ (no on-the-job search) and $F(T) = 1$ (all job offers are accepted), then $G(t) = F(t)$, so the commuting distribution function is equal to the employment distribution function. In case of the absence of on-the-job search ($k = 0$) but not all job offers are accepted, $G(t) = F(t)/F(T) = F(t|t \leq T)$ for $t \leq$ T. So, the observed commuting distribution function is equal to the *conditional* employment distribution function, the condition being that the unemployed only accept offers within a certain range defined by T.

For simplicity, suppose now that $\lambda_0 = \lambda_1$, so, as we have seen above, T = (w-b)/η (see (5)). In this special case, T does not depend on k. It follows that $\partial E(t)/\partial k < 0$, since $E(t|t < T)$ depends negatively on $G(t)$.[9] Hence, the expected commuting distance is a negative function of k, the ratio of the employed arrival rate λ_1 and the dismissal rate δ. This result is interesting, since it has been often claimed that low levels of flexibility in the labour market may reflect upon longer average commuting distances, the idea being that workers have more opportunities to reduce the commuting distance given higher job arrival rates (see e.g. Van

Ommeren, 2000, p. 7). To the extent that higher job arrival rates are associated with higher dismissal rates, this claim is false.

Further, it follows that $\partial G(t)/\partial F(t) = [k + F(T)^{-1}]f(t)/[1 + kF(t)]^2 > 0$. Hence, an increase in the employment density $F(t)$ shifts the commuting distribution. The effect of an increase on the expected commuting distance is ambiguous, because T depends on F(t). In case that $\lambda_0 = \lambda_1$, T does not depend on $F(T)$, thus $\partial E(t)/\partial F(t) < 0$. So, the model predicts then that ample (regional) job opportunities reduce the expected commuting distance. This prediction is in line with the spatial mismatch hypothesis and empirical evidence (e.g. Van Ham et al., 2001b).

Our main result of interest is that we will demonstrate that, given on-the-job mobility (so $k > 0$) and presuming two-dimensional space, unimodal commuting density functions are obtained which are in line with empirical research. In contrast, the assumption of one-dimensional space generates a monotonically increasing density function, which is inconsistent with empirical evidence.

So, let us first presume that space is one-dimensional. Given one-dimensional space, $F(t) = \alpha t$ and thus $F(t)/F(T) = t/T$, so it follows from (8) that:

$$G(t) = \frac{(T^{-1} + k\alpha)t}{1 + k\alpha t} \text{ and } g(t) = \frac{T^{-1} + k\alpha}{(1 + k\alpha t)^2}, \tag{9}$$

where $g(t)$ denotes the commuting density function. It follows that the commuting density function $g(t)$ is strictly decreasing in t for $k > 0$ ($g'(t) < 0$ for $k > 0$). See Figure 1, for $k = 3$, $\alpha = 1$ and T = 1. This shape of the density function is not in line with empirical evidence, which shows that the commuting density function is *not* strictly decreasing. One of the stylised facts in the literature is that the density function is unimodal. Notice further that if on-the-job mobility is absent, so $k = 0$, then $G(t) = t/T$, so the density commuting function is homogeneous, which is also not consistent with the empirical literature.[10]

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[9] $E(t \mid t < T) = \int_0^T tg(t)dt = T - \int_0^T g(t)dt = \int_0^T [1 - G(t)]dt.$

[10] Our analysis is partial in the sense that employment is exogenously given. One can endogenise the relative measure of firms as reflected in α, by assuming a flow of revenue generated per employed worker p > w, the existence of a positive fixed costs c > 0 for creating a vacancy and invoking free entry (Burdett and Mortensen, 1998). Population density is denoted as γ. In this case, given one-dimensional homogeneous space, an employer's steady-state profit given entry at an arbitrary location equals $(p-w)\gamma(1-u)/\alpha = c$, where $\gamma(1-u)/\alpha$ denotes the number of employed persons per firm. Given (6) and $F(T) = \alpha T$, one obtains: $\alpha = (\gamma(p-w)-\delta/\lambda_0 T)/c$. Hence,

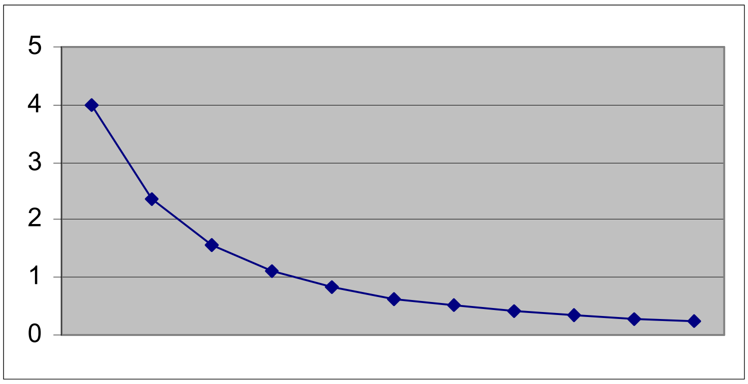

Figure 1. Commuting density presuming one-dimensional space (k = 3)

Now suppose that space is two-dimensional. Given two-dimensional space, $F(t) = \beta t^2$ and thus $F(t)/F(T) = t^2/T^2$. It follows from (8) that:

$$G(t) = t^2 \frac{T^{-2} + k\beta}{1 + k\beta t^2} \text{ and } g(t) = \frac{(T^{-2} + k\beta)2t}{(1 + k\beta t^2)^2}. \tag{10}$$

This commuting density function is unimodal for $k > 0$, given on-the-job mobility (for $k > 0$, $g'(0) > 0$ and $g''(t) < 0$). This shape of the commuting density function is in line with empirical evidence. See Figure 2, for $k = 3$, $\beta = 1$ and $T = 1$. Hence, it follows that the distinction between one- and two-dimensional space is empirically relevant. We emphasise that we need *two* assumptions to generate a unimodal commuting density function: we need the assumption of two-dimensional space combined with the assumption of on-the-job search.

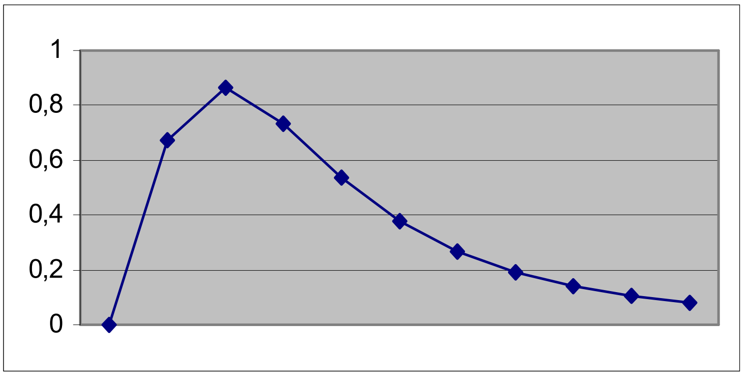

Figure 2. Commuting density presuming two-dimensional space (k = 3)

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employment density α depends positively on population density, profit generated per worker and T. The latter makes sense. If job seekers are willing to accept a job offer further away, then this creates additional employment opportunities.

One prediction of the model is that, *given two-dimensional space, the commuting density function must be increasing in it's argument for employees in their first job*.[11] For this group, $G(t) = F(t)/F(T) = t^2/T^2$, and therefore $g'(t) = 2/T^2 > 0$. To test the latter prediction, we have analysed the commuting density of employees in the Netherlands who left school less than one year before. For the large majority of these employees, this job will be the first job, so given the assumption of two-dimensional space, the commuting density must be increasing in it's argument. It appears however that the commuting density function of school-leavers is unimodal and very similar to the density function of other employees (see Appendix 2). Hence, although 'on-the-job mobility' may be relevant to our understanding of the shape of the commuting distribution, there must be other factors (as well), which contribute to the unimodal shape of the commuting distribution. Hence, in the sequel, we will concentrate on other factors that may explain the shape of the commuting distribution.

3. Spatially-varied search

Above we have presumed that the search decision does not involve any spatial component. The unemployed search with the same intensity everywhere. This is not intuitive, because job seekers are more likely to search in areas where the pay off of search is higher (or where the search costs are lower). Let us presume therefore that the arrival rate can be varied over space by job seekers, where space is defined by the distance t_x of travelling between the residence location and the *location of search*. For simplicity, we presume the absence of on-the-job mobility. We presume that the spatially-varied arrival rate of jobs at t_x, denoted as λ, is an increasing and strictly concave function of search intensity s ($s \geq 0$) at that location. Hence, the arrival rate at t_x depends on the (optimally chosen) search intensity at t_x. So $\lambda = \lambda(s(t_x))$, where $\partial\lambda(s(t_x))/\partial s > 0$ and $\partial^2\lambda(s(t_x))/(\partial s)^2 < 0$. Further, $\partial\lambda(s(t_x))/\partial s = \infty$ for $s = 0$. For example, one functional form of $\lambda(s(t_x))$ which is consistent with these assumptions is that $\lambda(s(t_x)) = \{s(t_x)\}^\gamma$, $0 < \gamma < 1$.

We suppose that the *marginal* search costs are constant over space and equal to c. The lifetime income of the unemployed and employed respectively can then be written as:

[11] Another prediction of the model is that the average commuting distance is a negative function of the elapsed employment time (the duration since becoming employed) and therefore of age if one does not control for the elapsed employment time. Such a prediction is in line with empirical studies (see e.g. Rouwendal and Rietveld, 1994; White, 1986).

$$rV_0 = b - c\int s(x)dF(x) + \int \lambda(s(x)) \max\{V_1(x) - V_0, 0\} dF(x) \tag{11}$$

and

$$rV_1(t) = w - \eta t + \delta[V_0 - V_1(t)]. \tag{12}$$

The unemployed job seeker will choose simultaneously the maximally acceptable commuting distance T and the optimal search intensity s.[12] The unemployed will never search at locations further than T. This implies that $s(t_x) = 0$ and $\lambda(s(t_x)) = 0$ for $t_x \geq$ T. The first-order condition for $s(t_x)$ can be written as:

$$-c + \frac{\partial \lambda(s(t_x))}{\partial s}\{\mathrm{V}_1(\mathrm{t}_\mathrm{x}) - V_0\} = 0 \text{ for } t_x < T\text{, else } s(t_x) = 0. \tag{13}$$

Hence, the marginal costs of search equals the marginal benefits of search at t_x. This equation implies that s is a negative function of t_x, because $\mathrm{V}_1(t_x)$ is decreasing in t_x. This makes sense: the unemployed searches more intensively at nearby locations (as reported by Rogers, 1997). As a consequence, $\lambda(s(t_x))$ is a negative function of t_x. For example, presuming the same functional form for $\lambda(s(t_x))$ as above ($\lambda(s(t_x)) = \{s(t_x)\}^\gamma$, $0 < \gamma < 1$) and using (13) then it can be shown that $\lambda(s(t_x)) = \{[V_1(t_x)\text{-}V_0].\gamma/c\}^{\gamma/(1-\gamma)}$ and thus:

$$\partial\lambda(s(t_x))/\partial t_x = -\eta[\gamma/(1-\gamma)][\gamma/c]^{\gamma/(1-\gamma)}\{V_1(t_x) - V_0\}^{\gamma/(1-\gamma)-1}/[\rho+\delta], \tag{14}$$

because $\partial V_1(x)/\partial t_x = -\eta/[\rho+\delta]$ according to (12). If $\gamma = ½$, then $\partial\lambda(s(t_x))/\partial t_x = -\eta/\{2c[\rho+\delta]\}$, so $\lambda(s(t_x))$ is linear in t_x; if $\gamma > ½$, $\lambda(s(t_x))$ is convex; if $\gamma < ½$, $\lambda(s(t_x))$ is concave. In the limiting case that γ approaches 1, the unemployed searches only at destinations with zero commuting distance; when γ equals zero, the unemployed searches with equal intensity over space within a range determined by T.

[12] The maximally acceptable commuting costs for the unemployed are defined by: $V_1(T) = V_0$.

The arrival rate λ as a function of the location of search t_x

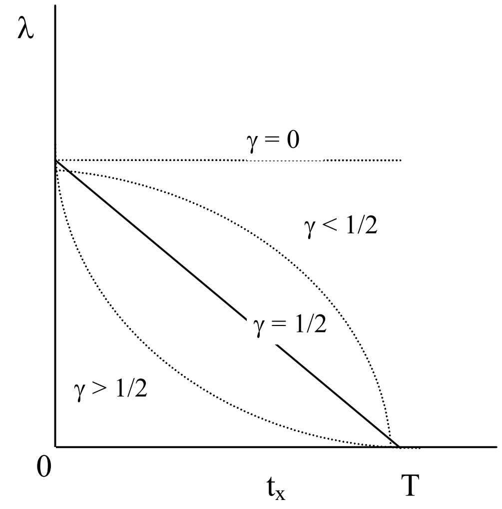

Figure 3.

As can be seen from the above figure, the shape of the spatially-varied arrival rate depends crucially on the parameter value of γ, which determines the marginal arrival rate of jobs at a location t_x with respect to search effort at t_x. In case that γ approaches zero, the marginal arrival rate with respect to $s(t_x)$ is small, so workers become footloose (within a range determined by T) and if γ becomes (close to) one then the commuting distance (which is the result of search frictions) becomes negligible, so $g(t) = 0$ for $t > 0$. Interestingly, it has been argued for a while that workers are essentially footloose (e.g. Hamilton, 1982, 1989), so γ is small, but the current literature disputes this conclusion quite strongly (see e.g. Small and Song, 1992; White, 1999), so essentially arguing that γ is quite large. Later on, we will provide empirical evidence based on the shape of the commuting distribution, which suggests that γ must be substantially larger than ½.

Given homogeneous allocation of jobs and residences and given the initial allocation of workers to firms, the number of employed workers at a commuting distance greater than t and which are fired, equals $[1-G(t)](1-u)$. This number must be equal to the number of unemployed who find employment at a distance greater than t. This implies that:

$$[L(T) - L(t)]u = \delta[1 - G(t)](1 - u), \tag{15}$$

where $L(t)$ is the *weighted* cumulative employment density function, the weights being the spatially-varied arrival rates. $L(t)$ is defined as follows:

$$L(t) = \int_o^t \lambda(s(x)) f(x) dx \,. \tag{16}$$

Hence, the left-hand side of equation (15) describes the flow (at a certain time) of unemployed workers into employment at a distance greater than t, whereas the right-hand side represents the flow out of unemployment into jobs at a distance greater than t. Further, $u = \delta/[\delta + L(T)]$. Hence, substituting u into (15), $G(t)$ can be written as:

$$G(t) = \frac{L(t)}{L(T)} \text{ for } t \le T, \tag{17}$$

so the commuting distribution G(t) is fully defined by the spatially-varied arrival rate $\lambda(t)$ and the employment density f(t).[13] It follows further that the commuting density function $g(t)$ is defined by:

$$g(t) = \frac{\lambda(s(t)) f(t)}{L(T)} \,. \tag{18}$$

So, $g'(t) = [\lambda'(s(t))f(t) + \lambda(s(t))f'(t)]/L(T)$. This allows us again to examine the effect of assumptions on the dimensionality of space. Given one-dimensional space, $f(t) = \alpha$, and thus:

$$g'(t) = \alpha\lambda'(s(t)) / L(T) < 0 \,. \tag{19}$$

Hence, the assumption of spatially-varied search combined with the assumption of one-dimensional space generates a strictly decreasing commuting density function. Given two-dimensional space, $f(t) = \beta t$, and thus:

$$g'(t) = \beta[\lambda'(s(t))t + \lambda(s(t))] / L(T) \,. \tag{20}$$

[13] We have shown above that the spatial search activity at t_x is a negative function of the travelling costs between the residence location and the location of search t_x. This implies that $\partial\lambda(s(t_x)) / \partial t_x < 0$. The implication is that compared to non-spatially differentiated search strategies, $G(t)$ is larger everywhere, so the average commuting distance is smaller.

This expression implies that g(t) is not monotonic, because $g'(0) = \beta\lambda(s(0))/L(T) > 0$ and search intensity is zero at distance T, $\lambda(s(T)) = 0$, so $g'(T) = \beta\lambda'(s(T))T < 0$. If, in addition, we make the reasonable assumption that $\lambda(s(t_x)) = s^{\gamma}$ and $\gamma > ½$, so $\lambda(s(t_x))$ is convex in t_x, then $g''(t) < 0$ and thus $g(t)$ is unimodal. This additional assumption on $\lambda(s)$ guarantees then that, *given spatially-differentiated search strategies and two-dimensional space, the commuting density function is unimodal.*[14]

We will argue now that the commuting density functions as we observe them in reality seem inconsistent with the idea that job seekers search (almost) randomly within a certain range and are therefore footloose. Suppose that $\gamma = ½$ which implies, as shown above, that λ is linear in t_x. So, $\lambda(t_x) = \varepsilon_0 - \varepsilon_1 t_x$ $(\varepsilon_0, \varepsilon_1 > 0 \text{ and } \varepsilon_0 - \varepsilon_1 T = 0)$. Given two-dimensional space, this implies that $g'(t_x) = \beta[\varepsilon_0 - 2\varepsilon_1 t_x]/L(T)$ (see (20)). If $\gamma = ½$, $g(t)$ obtains it's maximum at $t = \varepsilon_0/2\varepsilon_1 = ½T$, so the mode is ½T. If we measure t in minutes travelled, then it must be true that for most workers T is within the range of 60 to 90 minutes, whereas the mode is close to 10 minutes, so the mode is *much* smaller than ½T. So, γ is substantially larger than ½ (see Figure 3). This indicates that increasing search effort at a certain location substantially increases the arrival rate of jobs (the arrival rate is thus a convex function of t_x). This strongly suggests that job seekers are *not* footloose within a certain range as has been suggested by the literature (e.g. Hamilton, 1982, 1989), but search more intensely for jobs closer to their residence (see Rogers, 1997).

4. Residential mobility

One major omission of the above models is the assumption of the absence of residential mobility. This raises the question what the effect is of residential mobility on the commuting distribution. We make therefore the assumption of complete information in the housing market (in line with the urban economics literature, but we ignore house prices since space is assumed to be homogeneous) and presume that the worker may move house at costs m ($m > 0$) and choose the residence location optimally. Zax (1994) argues that residential and job mobility may be substitutes or complementary, so we allow here for on-the-job mobility. Let H denote the probability of moving residence. The lifetime income of the unemployed can then be written as:

[14] This result is in line with empirical evidence discussed in the previous section, where has been shown that the commuting density (of school-leavers) is unimodal.

$$rV_0 = b + H\lambda_0(V_1(0) - V_0 - m) + \lambda_0 \int_0^{T^*} [V_1(x) - V_0] dF(x), \tag{21}$$

where $H = 1 - \int_0^{T^*} dF(x)$ and T* is defined as the minimum commuting distance which triggers a residential move of the unemployed. So, if t exceeds T*, the unemployed will move residence, and otherwise will not move.[15]

We relax now the assumption of homogeneous space, and presume that the unemployed individual searches *within* a *finite* homogeneous area with a radius larger than T*. In case of infinite homogeneous space, the arrival rate of acceptable jobs would be infinite, since every job offer is accepted. In this rather extreme case, all individuals are employed with a zero commuting distance (since the arrival rate of jobs that do not involve a residential move is finite), so a degenerate commute emerges.

$V_1(0)$ denotes the lifetime income *after* a residential move. So, in words, (21) states that the income associated with being unemployed is the sum of the unemployment benefit, the expected gain of moving job and residence simultaneously and the expected gain of moving job, but not moving residence. After a residential move, the commuting distance is zero. The lifetime income of an employed person can be written as:

$$rV_1(t) = w - \eta t + \lambda_1 \int_0^{t} [V_1(x) - V_1(t)] dF(x) + \delta(V_0 - V_1(t)). \tag{22}$$

Note that an employed person with a positive commuting distance will never choose to relocate residence, because the employed would at the moment of the job offer have exercised the option to move residence. In the case that the individual has moved residence, so $t = 0$, then (19) implies:

$$rV_1(0) = w + \delta(V_0 - V_1(0)). \tag{23}$$

[15] It can be seen that T* must be smaller than T as defined in Section 2. The proof is as follows. Presume that T* > T, so job contracts implying distances between T* and T will be rejected, whereas contracts implying distances larger than T* will be accepted. Such behaviour is clearly irrational, implying that T*≤ T. This makes sense intuitively. If individuals have the option to move residence, then the maximum observed commuting distance will be less compared to individuals who do not have this option.

So, the employed will only move job involuntarily. Let us focus now on the unemployed's decision to move residence. The unemployed worker will move residence when $V_1(0) - m \geq V_1(t)$. So, the value of T* is determined by the condition $V_1(0) - m = V_1(T^*)$. This latter condition can be used to determine T* (using integration by parts):

$$T^* = (r+\delta)m + \lambda_1 \int_0^{T^*} \frac{1-F(x)}{r+\delta+\lambda_1} dx, \tag{24}$$

since $\int_0^{T^*} [V_1(x) - V_1(T^*)] dF(x) = \int_0^{T^*} V_1^{'}(x)[1-F(x)]dx$. Note that $(r+\delta)m$ can be interpreted as the discounted capitalised moving costs, which depends on the dismissal rate δ, because the advantages of reducing the commuting distance depends on the expected time that the job will last (this has been suggested by Manning (2003) who does not model the residential moving decision). T* exceeds the discounted capitalised moving costs, $(r+\delta)m$, because the unemployed takes into account that in the future *when employed* another job offer may arrive closer to the residence which makes it less attractive to move residence now. Equation (24) may not necessarily solve for T* if *m* is too large.[16] In this case, the unemployed job seeker will never move residence (so we can use the model discussed in Section 2). In case of a solution, the unemployed worker will accept every job offer and will move residence when *t* exceeds T*. Derivation of the commuting distribution function is then straightforward. For $t > 0$, it follows that:

$$G(t) = 1 - \frac{1 - F(t)/F(T^*)}{1 + kF(t)} \quad \text{for } 0 < t \leq T^*. \tag{25}$$

Hence, for $0 < t < T^*$, $G(t)$ is proportional to the commuting distribution derived in Section 2 (see (8)), the factor of proportionality being $[k\text{-}F(T^*)^{-1}]/[k\text{-}F(T)^{-1}] < 1$. Hence, one of the relevant results is that *residential mobility does not fundamentally change the shape of the commuting distribution function for t > 0*. One difference is, of course, that $G(t) = 0$ for T* < *t* < T. Given residential mobility, the commuting density at distance 0 can be written as:[17]

[16] In case *m* approaches zero, T* approaches zero, so the commuting distribution becomes (close to) degenerate.

$$G(0) = g(0) = 1 - F(T^*) . \tag{26}$$

So, it follows that the commuting density at distance 0 equals the probability that the unemployed moves residence given a job offer. This implies that, given perfect information on the housing market, one should observe a masspoint at t = 0. Such a masspoint is not observed in the data for workers. These results suggest that residential mobility is not a determining factor to explain the shape of the commuting distribution.[18]

5. Heterogeneity

In the previous sections, we have assumed that all jobs are identical (apart from the workplace location). Such an assumption is in contrast to the idea that heterogeneity of jobs may be relevant. In the current section, we presume that jobs differ with respect to the wage offered to the job seeker. A priori, the job seeker does not know the wage associated with a certain job, but knows only the wage distribution. Hence, we suppose the existence of a wage offer distribution F_w. We ignore on-the-job mobility (see Van Ommeren, 1998; Manning, 2003).

We will use the subscript *x* as an indicator of a characteristic on offer. Suppose the existence of a minimum wage offer, which will induce the unemployed to accept a job offer at distance t_x, the so-called reservation wage, denoted as *res*. Clearly, the reservation wage, *res*, is a positive function of t_x. So, a job offer will be accepted for which holds that $w_x > res(t_x)$. Let P denote the probability that an unemployed job seeker accepts a job, which can be written as:

$$P = \int_{res(t_x)}^{\infty} \int_{0}^{\infty} dF(t_x) dF_w(w_x) . \tag{27}$$

Let Q(t) denote the probability that an unemployed will accept a job *at a commuting distance less than t* (so, $w_x > res(t_x)$ *and* $t_x < t$):

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[17] The commuting density at distance 0, g(0), can be derived by noting that $\lambda_0[1-F(T^*)]u = \delta g(0)[1-u]$. Further, $u = \delta/(\delta+\lambda_0)$.

[18] There may be other reasons why such a masspoint is not observed. For example, space is not homogeneous, residences are not homogeneous, information on residence is not perfect, the presence of two-earner households, which all induce workers to accept a positive commuting distance when moving residence.

$$Q(t) = \int_{res(t_x)}^{\infty} \int_{0}^{t} dF(t_x) dF_w(w_x) . \tag{28}$$

In the steady state, there must hold that: $\lambda u Q(t) = \delta G(t)(1\text{-}u)$ and $u = \delta/(\delta+\lambda P)$, so the commuting distribution can be derived: $G(t) = Q(t)/P$. Hence:

$$g(t) = G'(t) = \int_{res(t)}^{\infty} f(t) dF_w(w_x)/P = f(t) \int_{res(t)}^{\infty} dF_w(w_x)/P , \tag{29}$$

where the last step follows from the independence assumption of w_x and t_x. Hence, $g(t)$ can be written as the employment density $f(t)$ times the conditional probability of accepting a job at t, the condition being that the unemployed accepts a job offer. A similar result has been obtained by Rouwendal and Rietveld (1994) who do not use a steady state utility maximising framework.[19]

As before, we investigate the effect of the assumption of the dimensionality of space on the commuting distribution. Presuming one-dimensional space, $f(t)$ is a constant which does not depend on t, but presuming two-dimensional space, $f(t)$ is increasing in t. As can be easily seen, the conditional probability of accepting a job at t is decreasing in t (since *res* is increasing in t_x). This is intuitive, because for jobs at larger distance, the probability that the wage exceeds the reservation wage is reduced. In case *res* is linear in t_x, then $g''(t) < 0$ whereas $g'(0) > 0$, so g is unimodal. So, *the combination of two-dimensional space and heterogeneity of jobs (e.g. wage heterogeneity) may explain the unimodal form of the commuting density function.* In contrast, presuming one-dimensional space, the form cannot be explained.[20]

6. Non-homogeneous space

Above we have presumed that space is homogeneous. Given the basic labour market model, presuming one-dimensional space and presuming the absence of on-the-job mobility, it

[19] Rouwendal and Rietveld (1994) do not obtain the division by P in their derivation of the commuting distribution.

[20] One may argue that the shape of the empirical commuting density function is the consequence of the heterogeneity of *workers* (and not of jobs) who differ in terms of age, education etc. For example, if the commuting density is strictly increasing until T, but employees have different values for T, a unimodal distribution may emerge. This idea can easily be tested based on a regression of commuting time on a range of explanatory variables. It has been often shown that the predictive power of explanatory variables is low (see e.g.

appears that $g(t) = T^{-1}$, so the commuting density function is homogeneous. We examine here to what extent the homogeneity of space assumption is relevant. This assumption was introduced because it simplified the analysis to a large extent: it allows us to ignore spatial variation in employment density, and therefore variation in expected income and house prices. It may be thought however that the shape of the commuting density function is mainly the result of the non-homogeneity of the employment density. In contrast, we show here that if the non-homogeneity is not too strong (viz., employment density can be thought to be linearly changing over space), the commuting density function at each residence location can still be approximated by a uniform distribution.[21]

Here, we presume homogeneous residences with an endogenously determined house price. Space is unidimensional and defined as a long finite line, so we can ignore boundaries. The residence location on this line is denoted with s. The job seeker may search 'upstream', so the location of the workplace is at $s+x$, where x may be positive or negative, and the commuting distance t equals $|x|$. Because we ignore boundaries, we may presume that $s-t > 0$. We ignore spatial variation in wages.

We denote by V_{0s} and V_{1s} the expected income of the unemployed and employed located at a location s respectively. The employment density does *not* depend on the location of the individual, which is denoted as $F(s+x)$. Hence, similar to (1):

$$rV_{0s} = b - R(s) + \lambda_0[\int \max\{V_{0s}, V_{1s}(x)\} dF(s+x) - V_{0s}] \tag{30}$$

and

$$rV_{1s}(t) = w - \eta t - R(s) + \delta(V_{0s} - V_{1s}(t)), \tag{31}$$

Given a location s, the unemployed will only accept jobs between $s-T_s$ and $s+T_s$. Note that the optimally chosen maximum distance T_s is not dependent on the 'direction' of the job search (upstream or downstream). So, (30) can be rewritten as:

White, 1986), so the expected commuting times of different types of employees are close to each other, and therefore the maximum commuting times are close to each other. So, this interpretation can be rejected.

[21] Note that we presume one-dimensional space. There is no reason to believe that in case of two-dimensional space, qualitatively different results are obtained.

$$rV_{0s} = b - R(s) + \frac{\lambda_0}{r+\delta}\int_{-T_s}^{T_s}[w - \eta\,|\,x\,| - R(s) - rV_{0s}]f(s+x)dx\,. \tag{32}$$

We presume that the existence of moving costs implies that individuals choose a location which includes one spell of unemployment and one spell of employment (see, similarly, De Salvo and Eeckhoudt, 1982). The optimal location is chosen when the individual is unemployed. Competition for residences between individuals guarantees that all unemployed individuals enjoy the same level of income, so $V_{0s} = V_0$, where V_0 denotes now the equilibrium lifetime income level which we presume to exist.[22] Unemployment at location s, u_s, is now defined by:

$$u_s = \frac{\delta}{\delta + \lambda_0 \int_{-T_s}^{T_s} dF(s+x)} = \frac{\delta}{\delta + \lambda_0[F(s+T_s) - F(s-T_s)]}\,. \tag{33}$$

Finally, T_s is endogenously determined by $V_0 = V_{1s}(T_s)$, so $T_s = [w\text{-}R(s)\text{-}\rho V_0]/\eta$, and, given (32):

$$T_s = \frac{w-b}{\eta} - \frac{\lambda_0}{r+\delta}\int_{-T_s}^{T_s}[T_s - |\,x\,|]f(s+x)dx\,. \tag{34}$$

In case of non-homogeneous space, the commuting distribution depends on the residence location s of the individual and will be denoted as $G_s(t)$. In the steady state, the commuting distribution is then defined by:

$$\lambda_0[F(T_s+s) - F(t+s) + F(s-t) - F(s-T_s)]u_s = \delta[1 - G_s(t)](1-u_s) \tag{35}$$

and hence using (33), this implies that:

[22] The optimal location is then determined by the maximum land rent that the individual is ready to pay to reach the equilibrium lifetime income level. This bid rent can easily be derived but does not play any role in further analysis.

$$G_s(t) = \frac{F(s+t) - F(s-t)}{F(s+T_s) - F(s-T_s)} \quad \text{for } t \le T_s. \tag{36}$$

Hence, the commuting distribution $G_s(t)$ is fully determined by the employment density function F(.).

Presume now that the employment density function depends linearly on s. So, $f(s) = \alpha s$ and thus $F(s) = ½\alpha s^2$. The employment density function takes this form if the employment density varies linearly over space, which is probably a good approximation for most individuals. This implies that:

$$G_s(t) = \frac{(s+t)^2 - (s-t)^2}{(s+T_s)^2 - (s-T_s)^2} = t / T_s \quad \text{for } t \le T_s. \tag{37}$$

Maybe surprisingly, we have shown that, given the assumption that the number of jobs per distance unit is linearly increasing over space, *the commuting distribution at each location is uniform. Hence, we obtain a similar result as given homogeneous* space (see (9), and impose $k = 0$*)*. This result is intuitive, since job seekers search randomly in two directions: 'downhill' and 'uphill'. The uphill employment density slope is positive, but the downhill slope is negative, so on average the slope is zero. In case that λ_0 is sufficiently, then T_s does hardly vary with s (see (34)), and the uniform distribution is probably a good approximation for a sample of commuters at different residence locations. Hence, the overall conclusion is that non-homogeneity of space does *not* have a strong effect on the form of the commuting density function. This may explain why samples of workers in different countries generate similar commuting density functions although the spatial structures of these countries are quite different.

7. Conclusion

In this paper we have analysed the commuting density function from a job search perspective. We have examined under which conditions the commuting density function appears to be unimodal which is one of the stylised facts of commuting. It appears that a necessary condition is that space is two-dimensional. Furthermore, one of the following ingredients is sufficient: on-the-job mobility, spatially-differentiated search or heterogeneity of jobs.

Residential mobility does not appear to explain the shape of the commuting density function as we observe it. We have shown that if the employment density varies linearly over space, the commuting density function obtains is not so different from the density function given homogeneous space, which may explain why the form of the commuting density function is similar in countries with a different spatial structure. Finally, we have argued that the empirical form of the commuting density function as we observe it is consistent with the view that job seekers search more intensively for jobs closer to their residence and are therefore not footloose within a certain commutable area.

Appendix 1: Homogeneous space: an empirical test

The assumption of homogeneous space, combined with the notion that space is two-dimensional, implies that the number of jobs N within a certain distance x is a quadratic function of the distance, so $N = \eta x^2$, where $\eta > 0$. This allows us to test the homogeneity assumption.

In the Netherlands, for almost all workers (93%), commuting time is less than 45 minutes, whereas the large majority of workers (84%) travel less than 30 minutes.[23] So, the area of search is within a range of 30, or 45 minutes for most job seekers. Within a range of 45 minutes (by car), the average number of jobs reached is observed to be 11.8 times higher than within a range of 15 minutes, whereas within a range of 30 minutes, the average number is 4.94 higher.[24] In case of perfect homogeneous space (and a road network which connects all jobs to all residences in a straight line), the ratio would have been 9 and 4 respectively, so just somewhat less than observed (see Van Ham et al., 2001). So, the homogeneous assumption seems reasonable for the Netherlands as has been argued by a number of studies.

This result does not only indicate that the homogeneous space assumption is quite good, particularly within the range of 30 minutes, it also shows that the number of jobs between 15 and 30 minutes is about 31% [((3.94-3)/3)] and between 30 and 45 minutes about 36% [(((11.8-4.94)-5)/5)] *higher* relative to the number within 15 minutes, compared to the theoretical perfect homogeneous assumption.[25] Hence, on average, residence location densities are *negatively* related to job location densities.

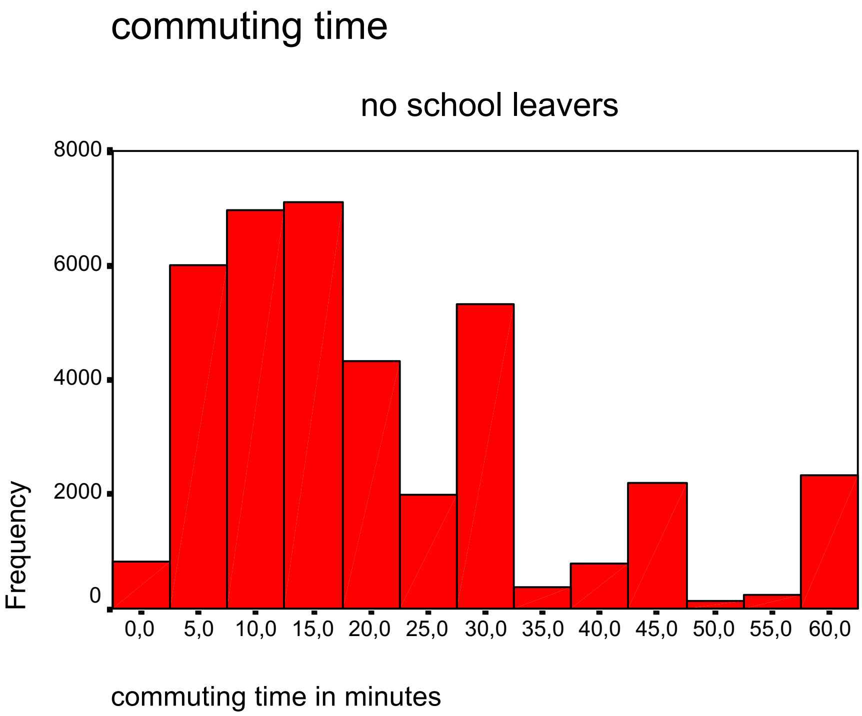
The above analysis of averages may mask large differences between individual zones. Analysis of individual postal code zone indicates however that residence location densities are also seldomly positively related to employment densities (exceptions are the centres of Groningen and Eindhoven, cities which are isolated with relatively little employment outside the city centre).

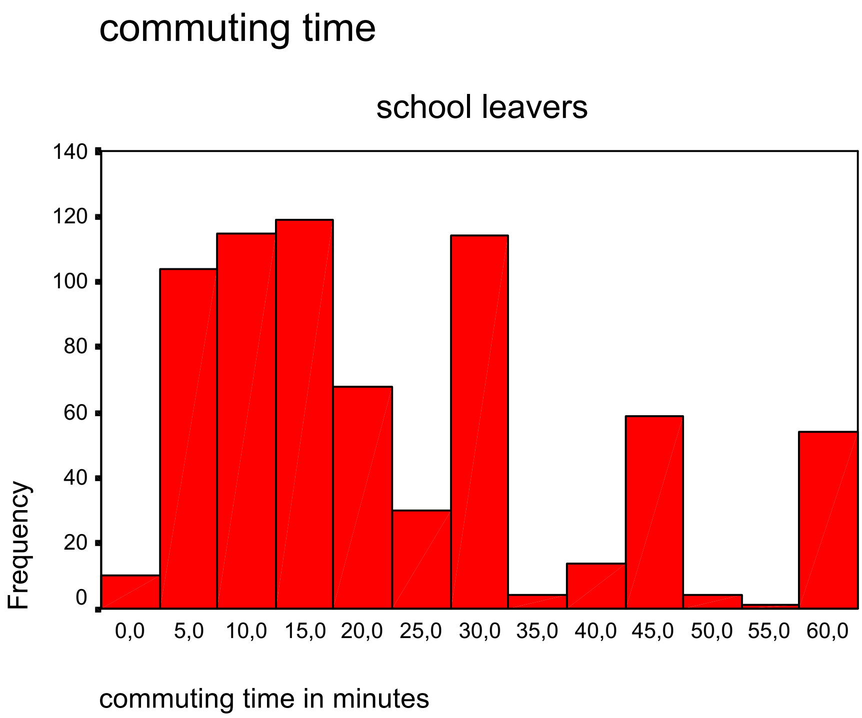
Appendix 2: Commuting density of school-leavers

We compare the commutes of school-leavers (employees who left school less than one year ago) with other employees based on the Dutch (1992) labour force survey. This survey does not distinguish between commutes of longer than 60 minutes, and are reported here as 60 minutes. From the figures it can be seen that there is a tendency to report rounded times

[23] These figures are comparable for most European countries, but also for example for the US.
[24] The study by Van Ham (1991) based on 4000 postal code zones in the Netherlands is used here.

(around 30 and 45 minutes specifically). Nevertheless, it is clear that the commuting density is *not* monotonically decreasing in it's argument.





[25] Given perfect homogeneous space, the ratio of jobs between 30 and 45 (between 15 and 30) to less than 15 equals 5 (3).

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